Photoionization of C^{2+} ions

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Photo*absorption* in the interstellar medium modifies the radiation spectrum of distant objects in the universe and thus complicates the interpretation of observations of such objects. Photo*ionization* of ions is an important mechanism for the production of highly charged ions in astrophysical plasmas exposed to hot sources of radiation. Ionization in such plasmas is usually balanced by low-energy electron-ion recombination. Because of their applied importance photon-ion and electron-ion collision processes have received long-standing interest by the plasma and astrophysics communities [1].

The pair of C^{2+} and C^{3+} ions is of particular interest for the understanding of astrophysical and man-made plasmas. Photoionization (PI) of C^{2+}

$$h\nu + C^{2+} \rightarrow C^{3+} + e \tag{1}$$

is the time-reversed (photo-)recombination (PR)

$$C^{3+} + e \rightarrow h\nu + C^{2+}. \tag{2}$$

Both reactions can proceed directly or in a multi-step fashion involving intermediate production of multiply excited autoionizing states. The indirect (resonant) PR channel is also called dielectronic recombination (DR). The principle of detailed balance, based on time-reversal symmetry, relates the cross sections of PI and PR on a state-to-state basis. Measuring one or the other of the two cross sections provides information about the time-reversed process. High resolution PR experiments with C^{3+} ions have been performed previously at heavy-ion storage rings [2, 3].

Here, we report on the first high-resolution PI experiments carried out with multiply charged ions at the Advanced Light Source (ALS). Our measurements are compared with state of the art theoretical calculations performed within the semi-relativistic Breit-Pauli R-matrix method. Absolute cross sections were determined at a number of selected energies by employing a suitable photon-ion merged beams technique. In addition, relative energy-scan measurements were carried out to cover a wide energy range in narrow energy

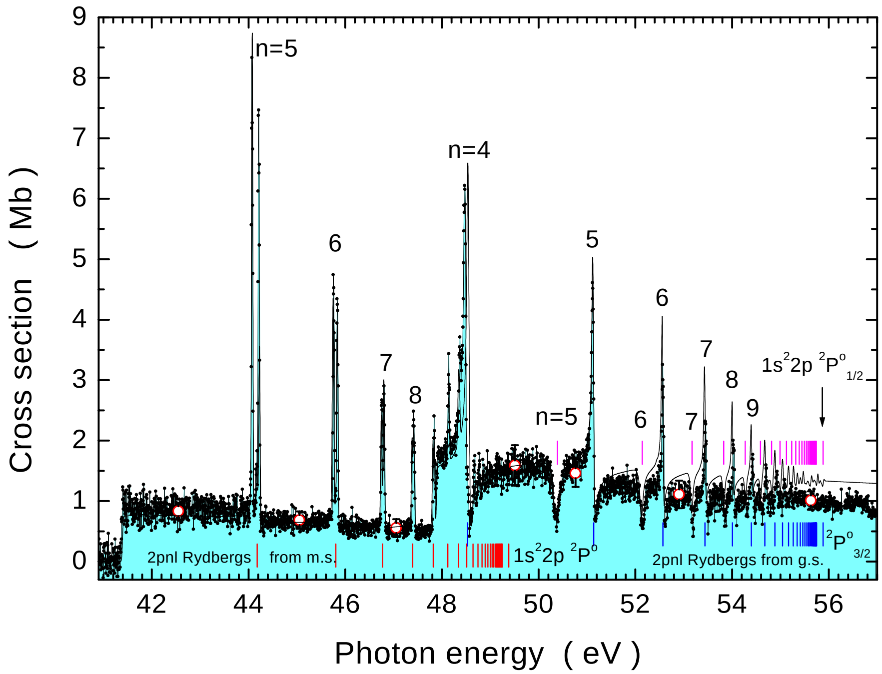

Figure 1: Measured and calculated cross sections for PI of C^{2+} ions. The energy-scan measurement is indicated by small dots connected by straight lines the area under which is shaded. The scan data were normalized to separate absolute PI cross section measurements (open circles with total error bars). The solid line represents the weighted sum of the R-matrix results assuming 60% of ground state (g.s.) ions in the primary beam, 30% in the $^3P_0$ and 5% each in the $^3P_1$ and $^3P_2$ metastable (m.s.) states. The theoretical result is almost indistinguishable from the measurements below 51 eV. The main Rydberg series of intermediate autoionizing states are indicated by vertical bars.

steps. The relative data were then normalized to the absolute cross sections. The C^{2+} target ions were produced with an all-permanent-magnet electron cyclotron resonance (ECR) ion source.

Fig. 1 shows an overview of the results obtained from the present experiment and theoretical calculations. The open circles represent the absolute cross sections. Total experimental uncertainties of these data are indicated by error bars. The normalized scan data are visualized by the shaded area. Theory is represented by a solid line obtained after convoluting the calculated results with a gaussian of 30 meV full width at half maximum. Excellent agreement between theory and experiment is obtained by assuming that the parent C^{2+} ion beam consisted of 60 % ground state ions and 40 % metastable ions (with 30% in the $^3P_0$ and 5% each in the $^3P_1$ and $^3P_2$ states). Almost perfect agreement of theoretical and experimental level energies is found.

Qualitatively, the PR experiments [3] show the same features as the PI data of Fig 1. The cross section is also dominated by $(2pnl)$ Rydberg resonances. Near threshold, i.e.

just above the (PI) ionization limit of C^{2+} and just above zero electron energy in the e + C^{3+} (PR) measurement the energy resolution is comparable in both the PI and the PR experiments. The resolution is sufficient to determine the natural line width of some of the states involved. Also the energy scales of both experiments agree very well within uncertainties of the order of less than 15 meV. However, the time-reversed PR measurement produces cross sections which are roughly two orders of magnitude above the present PI results. This apparent discrepancy may be understood in terms of how the data are obtained in the different experiments and how the related cross sections are defined. The PI experiment was carried out with a mixed beam of ground state and metastable ions. PI including the resonance contributions can populate the ground state of C^{3+} and at energies above 49.380 eV (for the metastable beam component) and 55.883 eV (for the ground state component) also the first excited states of C^{3+} which thus contribute to the measured cross section. In the storage ring PR experiments, however, only ground state C^{3+} ions were investigated. So there are contributions in the measured PI cross section that are not included in the PR data. The opposite is also true. Due to the relaxed selection rules for electron-ion collisions PR can populate many more autoionizing resonances than photoexcitation, which is essentially restricted to electric dipole transitions. In addition the PR resonances can decay to excited C^{2+} states which were not accessible to the PI measurements. In the light of this discussion it becomes clear that detailed balance has to be applied with care; it is valid only on a state-to-state basis. Consequently, PI and PR experiments nicely complement rather than duplicate each other providing additional information that would not be accessible by just one of the measurements. Branching ratios for different decay paths (or excitation pathways in opposite direction) of multiply excited states can be quantified by the comparisons. For example, the relative probability of the two-electron one-photon de-excitation of the $C^{2+}(1s^2 2p4d\,^1P)$ resonance could be inferred to be about 7.9 %.

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